NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

COMPONENT PERFORMANCE INVESTIGATION OF J71 EXPERIMENTAL TURBINE

III - EFFECT OF THIRD-STAGE SHROUDING ON OVER-ALL PERFORMANCE

By Donald A. Petrash, Harold J. Schum, and Elmer H. Davison

SUMMARY

A negligible effect on turbine efficiency and only a small decrease in turbine weight flow were observed when the J71 experimental turbine with 97-percent-design stator areas was modified to include shrouding of the third-stage rotor.

INTRODUCTION

The NACA Lewis laboratory is currently conducting a study of high-work-output low-speed multistage turbines. As a part of this research, a J71 experimental three-stage turbine is being investigated as a component under cold-air operating conditions. The over-all performance of this turbine and an evaluation of the internal-flow conditions and stage performance at equivalent design speed and work are presented in references 1 and 2, respectively. The latter investigation revealed that the efficiency of the third stage was significantly lower than that of the first or second stages, particularly in the blade tip region. The first and second turbine stages were shrouded, whereas the third stage was not shrouded and had a relatively large tip clearance. It was thought that the absence of a shroud and the large tip clearance might be contributing factors to the poor performance of the third stage.

The turbine was therefore modified by adding a shroud to the third-stage rotor. This change necessitated a small decrease in the annular flow area of the stator and rotor of the third stage. The blading for the first and second stages was the same as used in the investigation reported in reference 1. This modified turbine is hereafter arbitrarily called the J71-97 turbine, the -97 signifying that the stator throat areas are all approximately 97 percent of their design values.

The purpose of the subject report is to evaluate any change in over-all performance effected by the addition of the third-stage rotor shroud and the resulting decreases in the third-stage stator and rotor flow areas. The over-all performance characteristics of the J71-97 experimental turbine were determined, and the results are compared with those obtained for the original turbine (ref. 1).

SYMBOLS

The following symbols are used in this report:

E	enthalpy drop based on torque measurements, Btu/lb
g	acceleration due to gravity, 32.174 ft/sec^2
N	rotational speed, rpm
p	pressure, in. Hg abs
p_x'	rating total pressure, static pressure plus velocity pressure corresponding to axial component of velocity, in. Hg abs
R	gas constant, 53.4 ft-lb/(lb)($^{\circ}$R)
T	temperature, $^{\circ}$R
w	weight flow, lb/sec
$\frac{wN}{60\delta}\varepsilon$	weight-flow parameter based on product of equivalent weight flow and equivalent rotor speed
γ	ratio of specific heats
δ	ratio of inlet-air pressure to NACA standard sea-level pressure, $p_0'/29.92$ in. Hg abs
ε	function of γ, $\dfrac{\gamma_{sl}}{\gamma_e}\left[\dfrac{\left(\dfrac{\gamma_e+1}{2}\right)^{\frac{\gamma_e}{\gamma_e-1}}}{\left(\dfrac{\gamma_{sl}+1}{2}\right)^{\frac{\gamma_{sl}}{\gamma_{sl}-1}}}\right]$

η_i brake internal efficiency, ratio of actual turbine work based on torque measurements to ideal turbine work based on inlet total pressure p_0' and outlet rating total pressure $p_{x,7}'$

θ_{cr} squared ratio of critical velocity to critical velocity at NACA standard sea-level temperature of 518.7° R, $\dfrac{\dfrac{2\gamma}{\gamma + 1}\, gRT_0'}{\dfrac{2\gamma_{sl}}{\gamma_{sl} + 1}\, gRT_{sl}}$

τ torque, ft-lb

Subscripts:

e engine operating conditions

sl NACA standard sea-level conditions

x axial

0,1,2,
3,4,5, measuring stations (see fig. 3)
6,7,8

Superscript:

' total or stagnation state

APPARATUS, INSTRUMENTATION, AND PROCEDURE

The three-stage J71-97 experimental turbine test installation used in this investigation is the same as that used for the investigation of reference 1. A photograph of the over-all turbine experimental setup is shown in figure 1. The shrouding of the third-stage rotor was accomplished by grinding off the blade tip squealers, shrinking a 0.060-inch-thick metal band over these relieved blade tips, brazing the shroud to all the blades, and machining the outside diameter of this shroud to the desired shape. This resulted in an average third-stage rotor shroud-to-casing tip clearance of about 0.140 inch, compared with a measured value of approximately 0.120 inch for the unshrouded turbine (refs. 1 and 2). While these nominal tip clearances are considered large, they are required for the structural design. The actual shroud thickness was about 0.050 inch. This shrouding reduced the annular flow area of the third rotor 4 percent. In order, then, to maintain a smooth outer-shroud contour, the third-stator flow area was reduced by metal inserts at the blade tips. This latter change reduced the total stator-exit annular flow area 2 percent. The original third-stage blading configuration and the modifications to the third-stage blading incorporated for the subject investigation are shown schematically in figures 2(a) and (b), respectively. The first and second stages of the J71-97 turbine were the same as those in the original J71 experimental turbine (ref. 1).

The turbine equivalent design conditions are as follows:

Work, Btu/lb	32.4
Weight flow, lb/sec	40.3
Rotational speed, rpm	3028
Inlet temperature, ^{O}R	518.7
Inlet pressure, in. Hg abs	29.92

The method of deriving these equivalent design conditions is presented in reference 3.

The instrumentation used in the subject investigation is the same as that described in reference 1. A schematic diagram of the turbine showing the instrumentation is presented in figure 3. Measurements of total pressure, wall static pressure, and total temperature were taken at the turbine inlet (station 0) and at the turbine outlet (station 7). In addition, wall static taps were again provided on both the inner and outer shrouds ahead of each row of blades and at the tailcone exit (see fig. 3).

The turbine was operated at a nominal inlet pressure p_0' and temperature T_0' corresponding to 35 inches of mercury absolute and 700° R. A range of over-all total-pressure ratio from 1.4 to 4.8 was imposed across the turbine, and the speed was varied from 20 to 130 percent of equivalent design speed $N/\sqrt{\theta_{cr}}$.

The values of equivalent weight flow have been corrected for the fuel addition required to maintain the 700° R inlet temperature. Turbine efficiency is based upon the turbine-outlet pressure $p_{x,7}'$, which was calculated by adding the axial component of the velocity pressure to the average wall static pressure at the turbine-discharge measuring station. This axial component of velocity was computed from the turbine weight flow (air flow plus fuel flow), the known annular area at this measuring station, the measured total pressure, the total temperature, and the total- to static-pressure ratio. This calculated outlet pressure charges the turbine for the energy of the rotor-discharge tangential velocity; therefore, the values of brake internal efficiency η_i are conservative.

RESULTS AND DISCUSSION

3682 The over-all performance of the J71-97 experimental turbine is presented in figure 4. The variation of equivalent shaft work E/θ_{cr} with a weight-flow parameter $(wN/60\delta)\varepsilon$ is shown for lines of constant equivalent rotational speed $N/\sqrt{\theta_{cr}}$ and rating total-pressure ratio $p_0'/p_{x,7}'$. Also included are contours of constant values of brake internal efficiency η_i. The equivalent design operating point (equivalent design speed and equivalent shaft work (32.4 Btu/lb)), which is indicated, corresponds to a brake internal efficiency of 0.874. At increased values of equivalent speed and work, however, higher values of efficiency were obtained, a maximum value of 0.891 occurring at an equivalent shaft work of 38.3 Btu per pound and 130-percent equivalent design speed.

The efficiency of the J71-97 turbine is compared with that for the original J71 experimental turbine (ref. 1) in figure 5. Efficiencies are plotted against equivalent shaft work for rotor speeds of 70, 100, and 130 percent of equivalent design speed. In general, the efficiencies of the two turbines are comparable over most of the range of equivalent work investigated. At equivalent design speed and shaft work (fig. 5(b)), the efficiency of the J71-97 turbine (0.874) is close to the value of 0.877 obtained for the original turbine (ref. 1). Since the efficiency differences for the two turbines are so small (in general, less than 1 percent), it appears that the decrease in the flow areas in the third stage and shrouding the third-stage rotor had a negligible effect on the over-all turbine efficiency.

The variation of equivalent weight flow $(w\sqrt{\theta_{cr}}/\delta)\varepsilon$ with over-all rating total-pressure ratio is presented in figure 6. The zero slope of the curves for rotor speeds of 60 percent of equivalent design speed and above at the higher pressure ratios indicates that the turbine choked. Since the value of these choking weight flows decreases with increasing rotational speed, the turbine is obviously choking somewhere downstream of the first stator blade row. It was then considered of interest to determine which blade row was actually choked. Accordingly, figure 7 presents the ratio of static pressure to inlet total pressure p/p_0' at the different measuring stations as a function of over-all rating total-pressure ratio $p_0'/p_{x,7}'$ for design equivalent speed (similar to curves presented in ref. 1). Only the hub static pressures are presented herein, because they are considered the more critical insofar as choking in a blade row is concerned.

Figure 7 indicates that the hub static pressures for measuring stations 1 to 6 continually decrease with increasing over-all rating total-pressure ratio up to a value of 4.2. At higher pressure ratios, these static pressures are constant. However, the static pressure at station 7 continually decreases over the entire range of pressure ratio investigated. This indicates that the third rotor blade row choked at an over-all total-pressure ratio of 4.2. The same choking phenomenon was also noted for the third rotor of the original J71 experimental turbine (ref. 1) at the same pressure ratio. Preceding blade rows of the J71-97 turbine may choke simultaneously with the third rotor and result in constant static pressure ahead of the blade row. However, this possibility cannot be established from figure 7. It should be stated, however, that this choking pressure ratio of 4.2 is considerably higher than the pressure ratio at which equivalent design work was obtained at the equivalent design speed. The fact that the first stator is unchoked, as mentioned previously, is substantiated by the curves of figure 7, because the value of the static- to total-pressure ratio at measuring station 2 (behind the first stator) is well above the choking value of 0.528.

3682

If the performance map of the J71-97 turbine (fig. 4) is considered, it appears that the equivalent design operating point corresponds to a rating total-pressure ratio between 3.4 and 3.5. Figure 6 indicates that, at the equivalent design speed and in this range of pressure ratio, an equivalent weight flow slightly greater than 42 pounds per second was obtained. This weight flow is 4 percent greater than design (40.3 lb/sec, as indicated in fig. 6). At the corresponding operating point, the weight flow for the original J71 experimental turbine (ref. 1) was 5 percent greater than design. The 1-percent decrease in the weight flow for the J71-97 turbine is attributed to the decrease in the flow area of the third-stage stator and rotor.

The variation of equivalent torque $(\tau/\delta)\epsilon$ with over-all rating total-pressure ratio is presented in figure 8. Limiting loading was not obtained with the pressure ratios imposed across the turbine, as evidenced by the continual increase of torque with pressure ratio at all speeds investigated. The same characteristics were observed for the J71 turbine of reference 1.

In general, the over-all performance results of the J71-97 turbine were comparable with those of the original J71 experimental turbine (ref. 1). It can be concluded, then, that the addition of a shroud on the third rotor and the reduction of the flow area in the third stage had a negligible effect on turbine efficiency and only a small effect on the turbine weight flow.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the experimental J71 turbine with a shrouded third-stage rotor:

3682

1. A comparison of results from the experimental J71-97 and J71 turbines showed that, in general, the addition of a shroud on the third-stage rotor, with the corresponding reduction of flow area in the third stage, resulted in a negligible effect on over-all turbine efficiency and a slight decrease in the turbine weight flow.

2. At equivalent design speed and work, the turbine had a brake internal efficiency of 0.874 and an equivalent weight flow 4 percent greater than design.

3. The maximum efficiency of 0.891 occurred at 130 percent of equivalent design speed and an equivalent shaft work of 38.3 Btu per pound.

4. Limiting blade loading was not reached over the range of conditions investigated.

5. At equivalent design speed, the third-rotor row of blades choked at an over-all total-pressure ratio of approximately 4.2.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 29, 1955

REFERENCES

1. Schum, Harold J., and Davison, Elmer H.: Component Performance Investigation of J71 Experimental Turbine. I - Over-all Performance with 97-Percent-Design Stator Areas. NACA RM E54J15, 1956.

2. Rebeske, John J., Jr., and Petrash, Donald A.: Component Performance Investigation of J71 Experimental Turbine. II - Internal-Flow Conditions with 97-Percent-Design Stator Areas. NACA RM E54L16, 1956.

3. Rebeske, John J., Jr., Berkey, William E., and Forrette, Robert E.: Over-All Performance of J35-A-23 Two-Stage Turbine. NACA RM E51E22, 1951.

3682

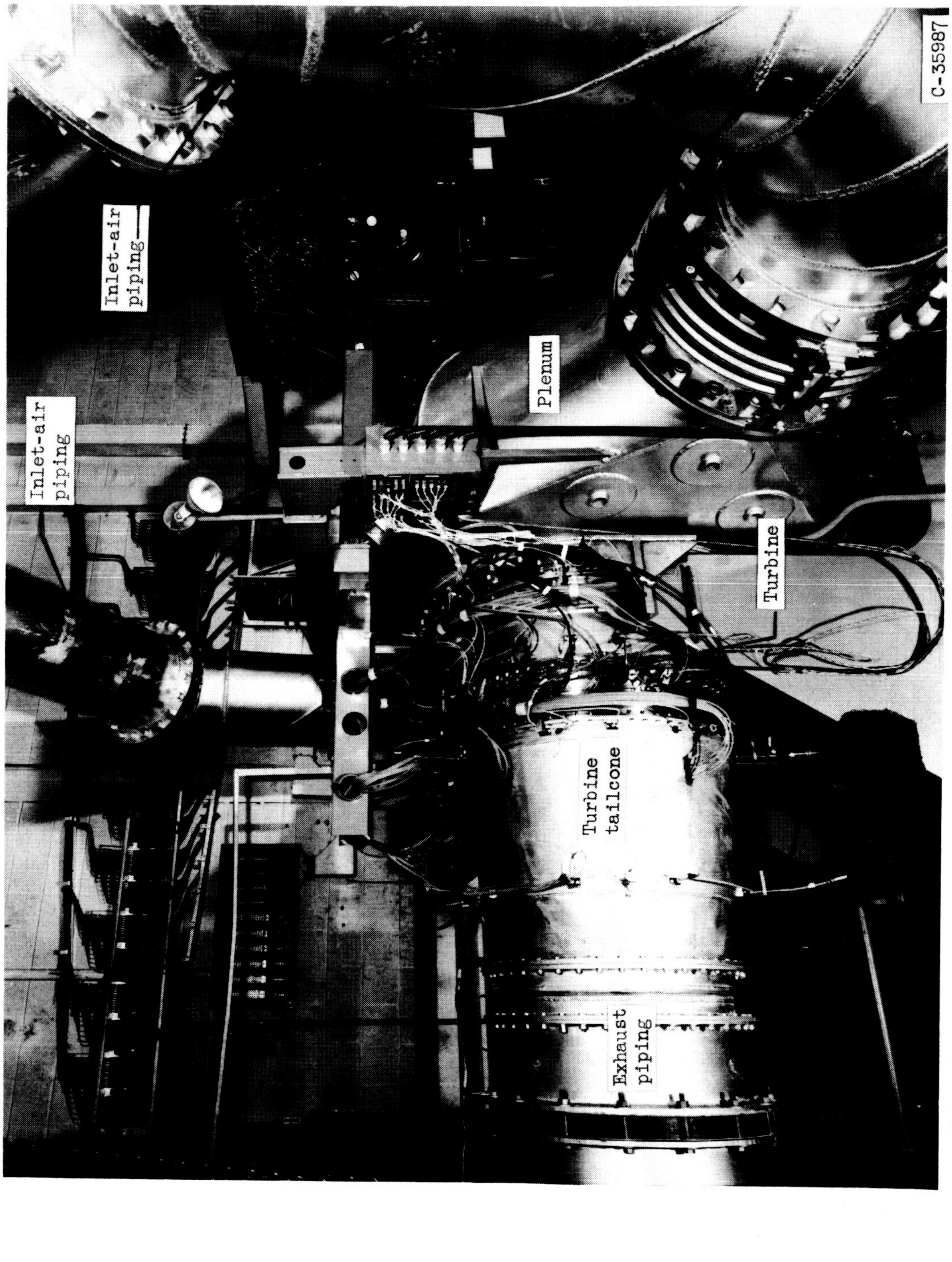
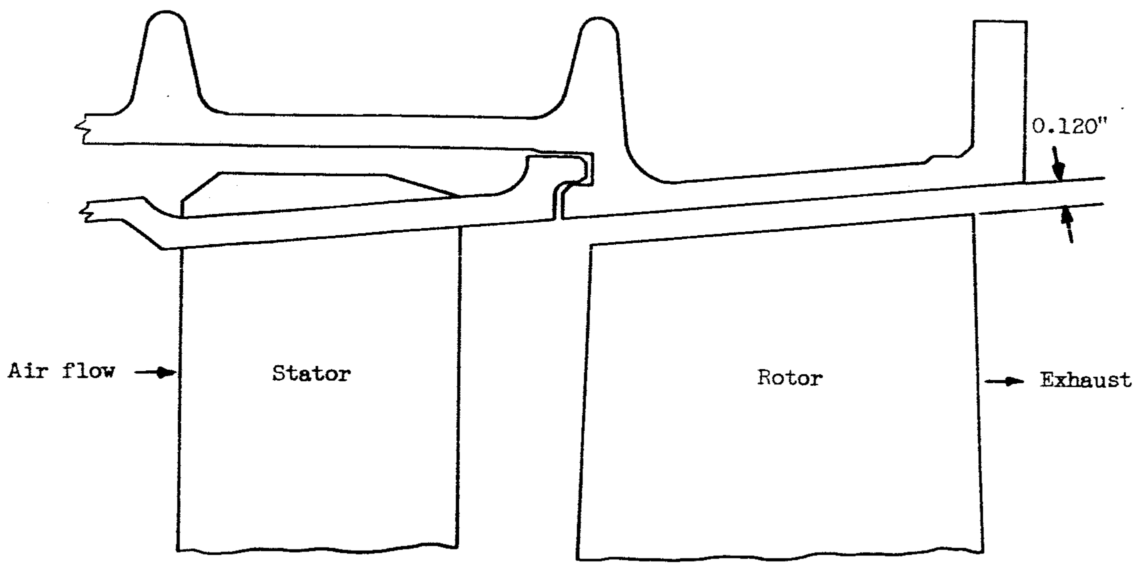
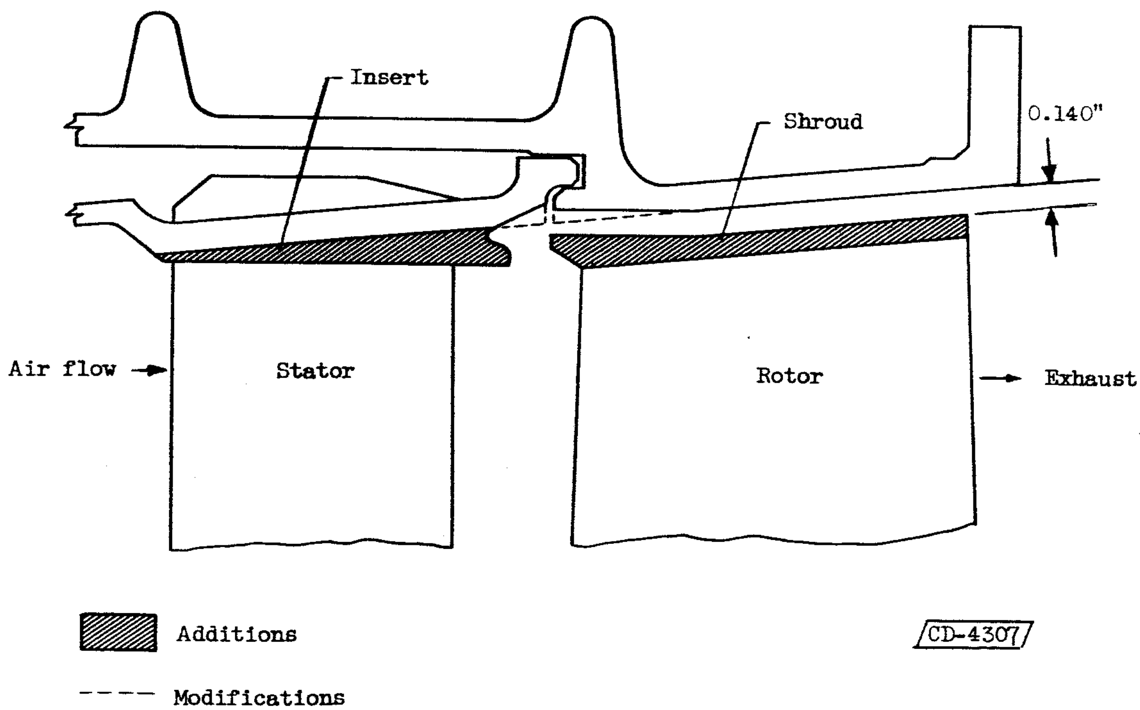


Figure 1. - Installation of experimental J71-97 three-stage turbine in full-scale turbine-component test facility.

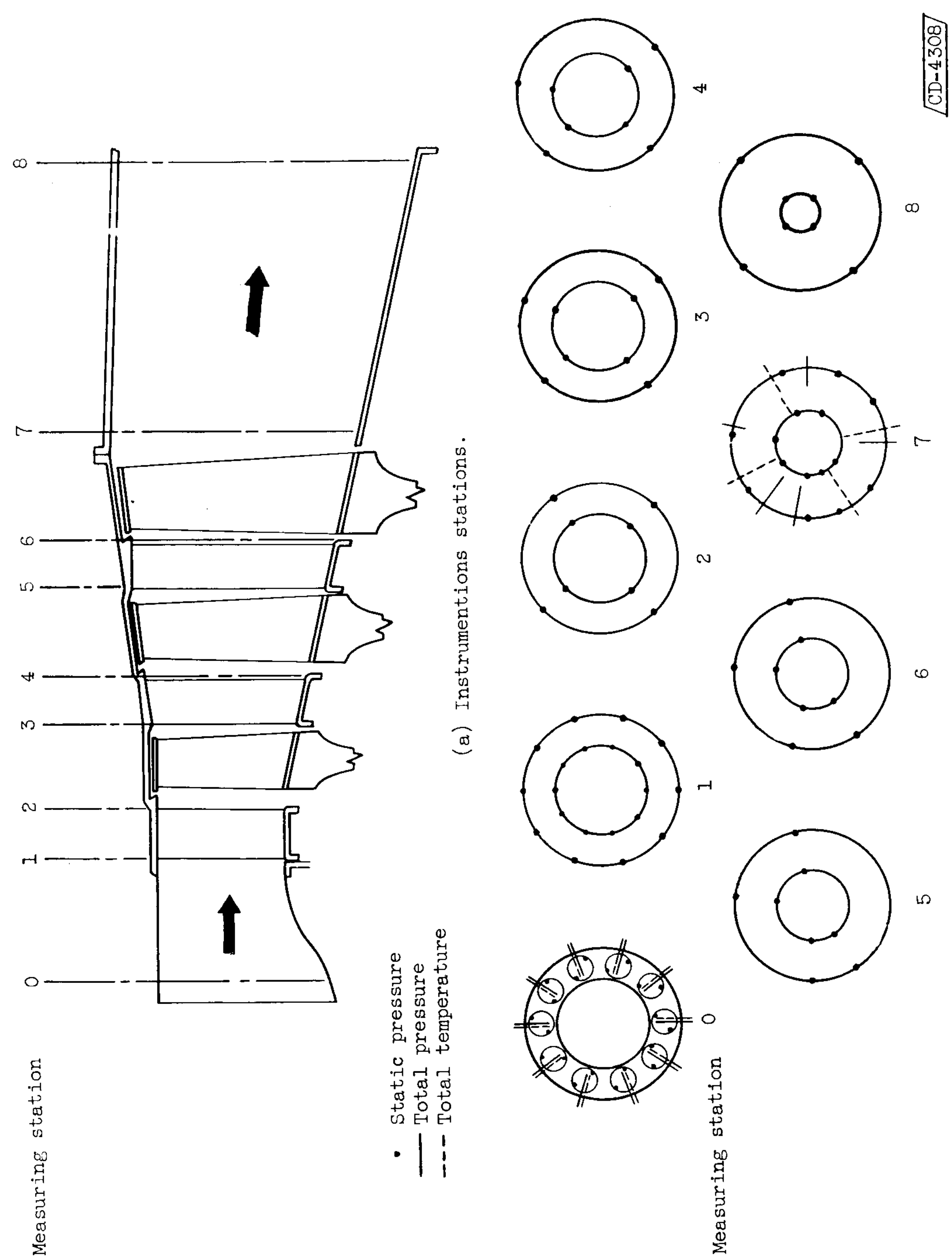


(a) Original unshrouded third-stage rotor configuration.



(b) Shrouded third-stage rotor configuration.

Figure 2. - Schematic diagram of third stage of J71 experimental turbine showing original and modified configurations.



(b) Circumferential location of instruments at each station.

Figure 3. - Schematic diagram of J71-97 experimental turbine showing instrumentation.

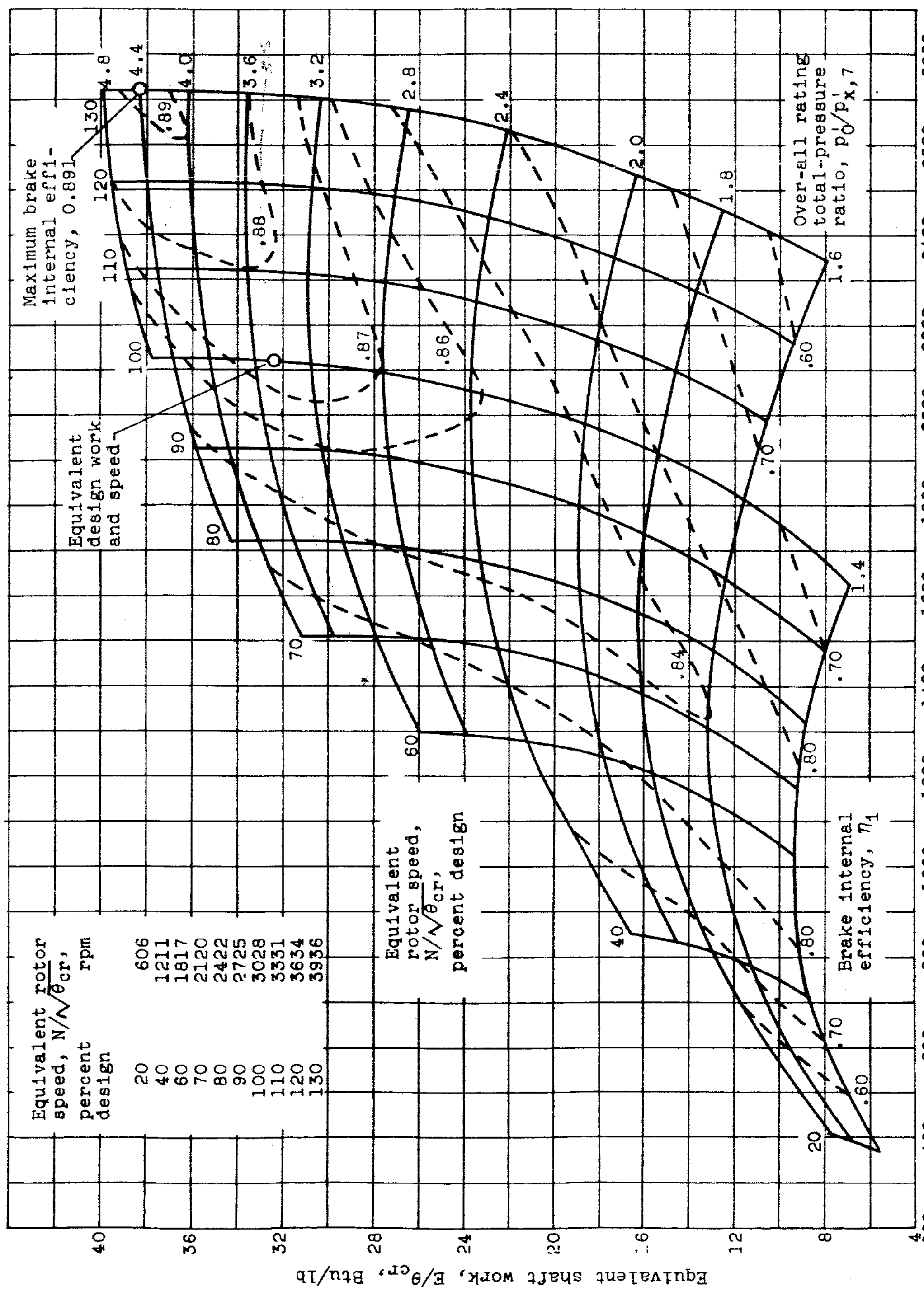
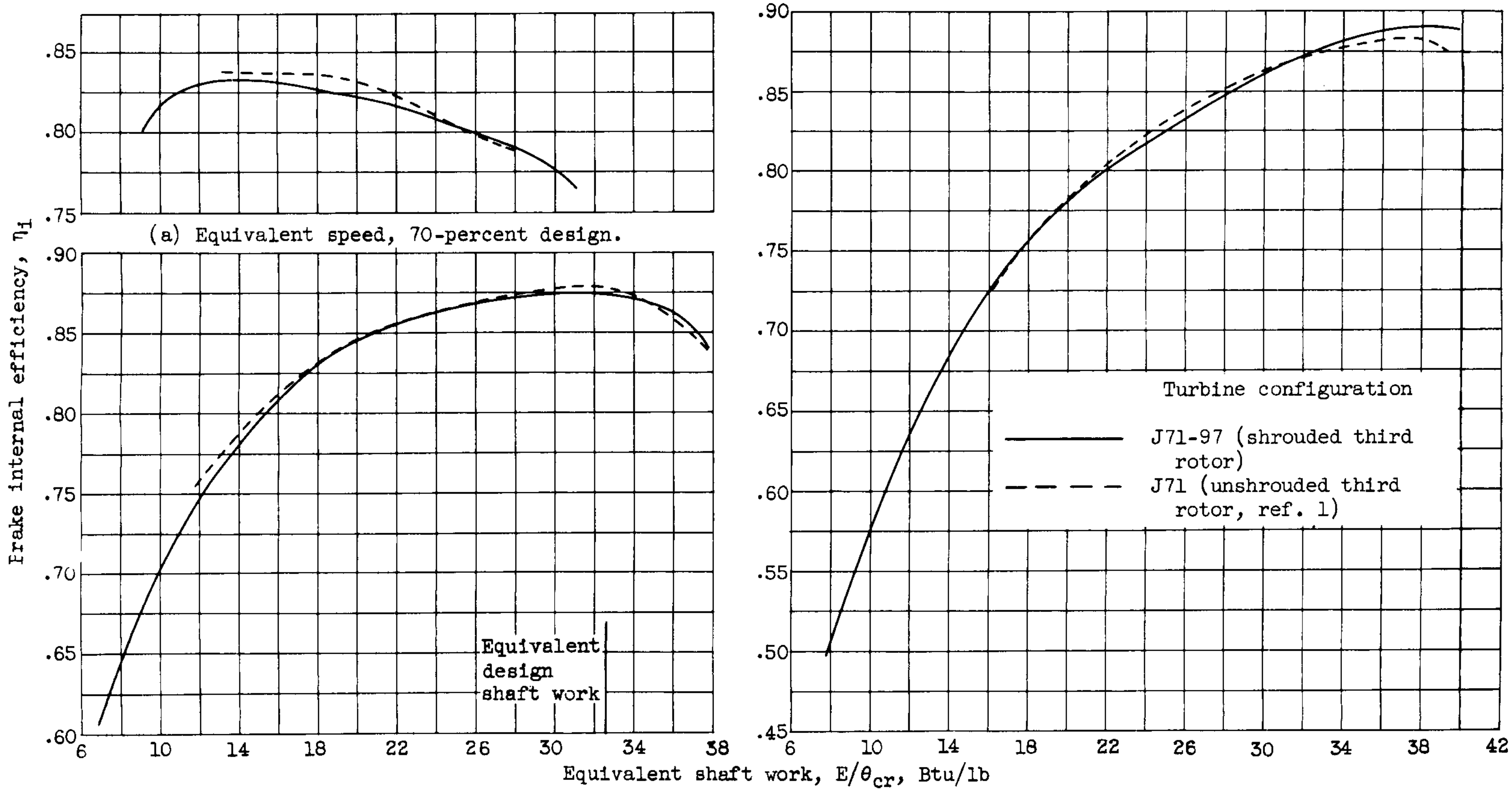


Figure 4. - Over-all performance of J71-97 experimental three-stage turbine. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

$E/\theta_{cr} = 32.4$

[redacted]



(a) Equivalent speed, 70-percent design.

(b) Equivalent speed, 100-percent design.

(c) Equivalent speed, 130-percent design.

Figure 5. - Variation of over-all turbine brake internal efficiency with equivalent shaft work at three rotational speeds for shrouded and unshrouded third-stage turbine configurations.

3682

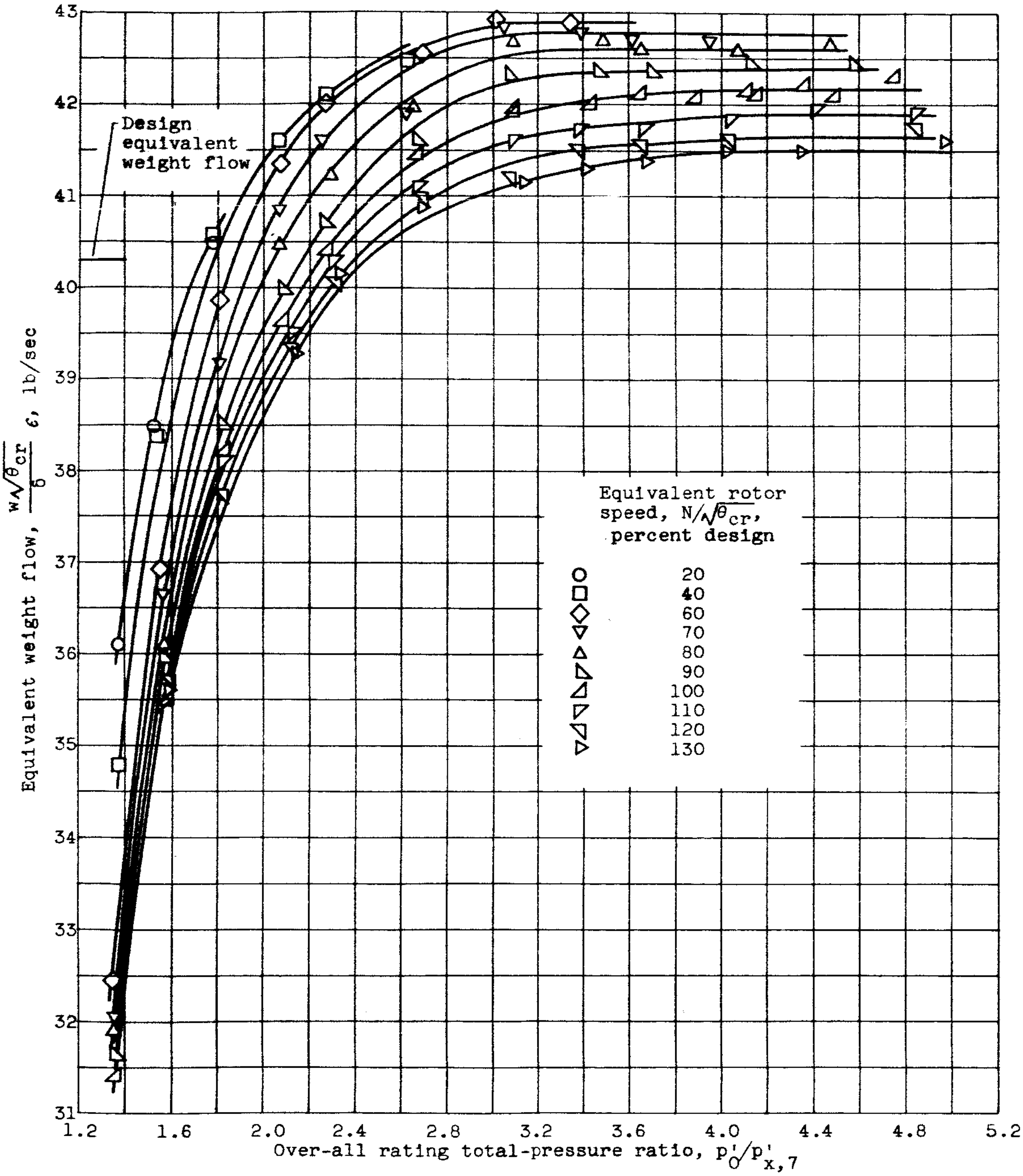


Figure 6. - Variation of equivalent weight flow with over-all rating total-pressure ratio for values of constant equivalent rotor speed.

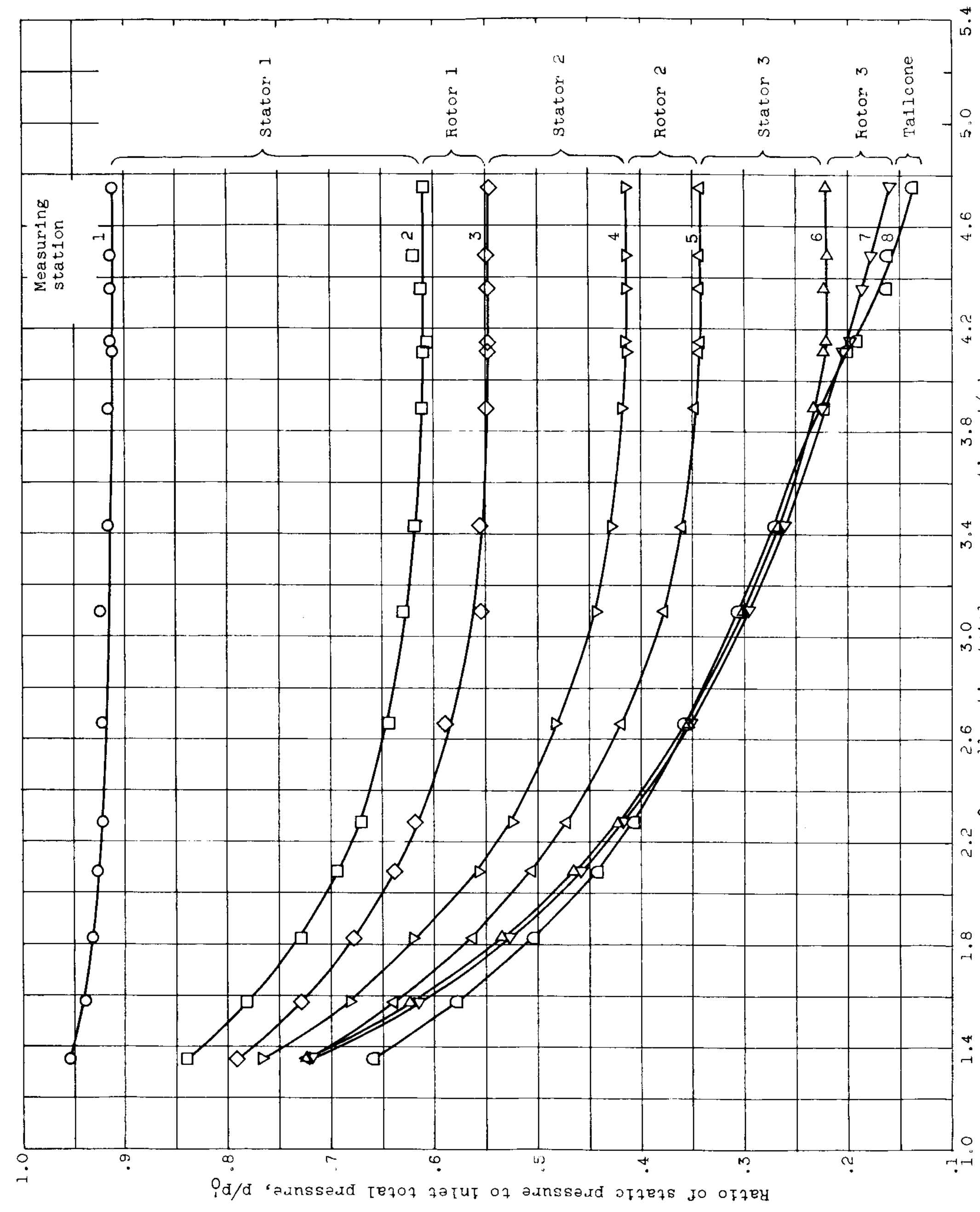


Figure 7. - Variation of static pressure at hub with over-all rating total-pressure ratio at different measuring stations for equivalent design speed.

3682

3682

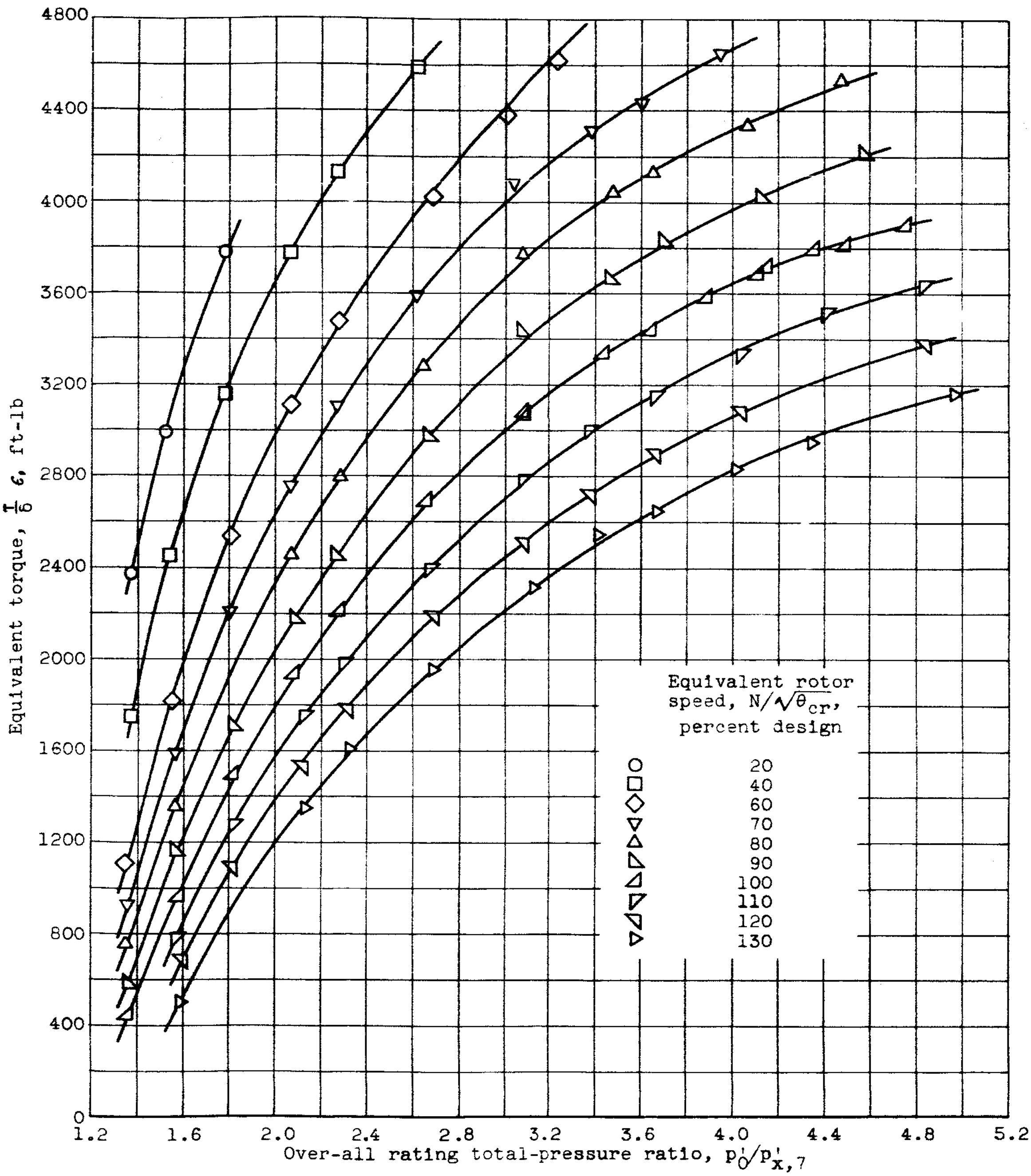


Figure 8. - Variation of equivalent torque with over-all rating total-pressure ratio for values of constant equivalent rotor speed.